CAREER: Near-field Imaging of materials dynamics processes at nanometer resolution

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<tr>
<th>Term</th>
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<tr>
<td>NFO probe</td>
<td>Conically shaped probe that serves to channel light through a small aperture</td>
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<td>before delivering it to a sample.</td>
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<td>Band-gap</td>
<td>Separation in energy between the highest electronic level of the valence</td>
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<td>band and the lowest level in the conduction band in a semiconductor. A</td>
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<td>well passivated perfect crystal does not have electronic levels across</td>
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<td>the band gap.</td>
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<td>Far-field optics</td>
<td>Simply another name for <strong>conventional optical microscopy</strong>—a lens-based</td>
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<td>imaging technique. The new terminology is used here to contrast its</td>
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<td>working principle with near-field optical microscopy. In conventional</td>
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<td>optical microscopy the working distance (the closest separation between</td>
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<td>the illumination device and the sample under analysis) is greater than</td>
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<td>the radiation wavelength ($\lambda$); its lateral resolution is not</td>
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<td>better than $\lambda/2$ (because of diffraction).</td>
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<td>Lateral resolution</td>
<td>Refers to the spatial resolution capability of a microscopy technique in</td>
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<td>the direction perpendicular to the incident light beam direction.</td>
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<td>Near-field Optics</td>
<td>Imaging techniques where the separation distance between the illumination</td>
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<td>(NFO)</td>
<td>source (typically an aperture of nanometer dimensions) and the sample</td>
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<td>is smaller than the radiation wavelength. Lateral resolution capability</td>
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<td>in NFO is finer than $\lambda/2$; it scales with aperture size of the</td>
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<td>scattering particle dimension.</td>
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<td>Optical Lithography</td>
<td>Well-established (far-field) optical technique widely used in the</td>
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<td>fabrication of micron-sized integrated circuits. Hampered by diffraction</td>
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<td>devices.</td>
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<td>Time-resolved</td>
<td>Additional characteristic of a microscopy technique to scrutinize the</td>
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<td>dynamics of physical processes.</td>
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<td>MEMS</td>
<td>Micro Electro Mechanical Systems. A is an evolving technology that</td>
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<td>capitalizes on the excellent mechanical characteristics of silicon to</td>
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<td>fabricate electro-mechanical actuators of micrometer dimensions</td>
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<td>Urban University</td>
<td>An institution that cultivates partnerships with regional community</td>
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A. GOALS and OBJECTIVES

Nanotechnology—molecular-level techniques aimed at fabricating nanometer-sized structures—is expected to revolutionize science and the global economy in the 21st century. Aiming to provide Portland State University students with the necessary skills and knowledge to develop new areas of nanotechnology, and to integrate into their education profile an international perspective and a commitment to vocational service toward society, this Career program will pursue the following goals:

- **Promote research and technological developments in Nano-Optics.** The central research theme of this Career application is imaging physical dynamic processes in materials at nanoscale lateral resolution, including carrier lifetime measurements in semiconductor nanostructures and rapid screening of macromolecules driven through micro- and nano-fluidic devices. Near-field Optics (NFO), a novel technique that operates beyond the $\lambda/2$ diffraction limit, will be used as the general technique platform to characterize nanostructures in a pump-probe modality. Research activities on the PSU campus and device fabrication (by PSU students) at the MEMS-foundry of the Washington Technology Center (WTC) will characterize this Career program.

- **Provide students with opportunities to acquire a multidisciplinary education,** including hands-on experience in Optics and Electronics (the backbone disciplines underpinning near-field optical microscopy), professional training on MEMS-device fabrication (at the WTC), internships (at the Applied Nanobioscience Center, Arizona State University), professional writing skills (at the PSU Writing Center), and service to society (disseminating knowledge in high school classroom settings).

- **Promote inter-institutional research collaboration.** At the national level this Career program will benefit from the committed support from the Silicon Wafer Engineering and Defect Science Center (SiWEDS) at North Carolina State University. The SiWEDS has, in addition to its seven participant universities, 11 industry members, which offers us a real opportunity to expand connections with the industrial sector. Similarly, we will deepen our collaboration with the Applied Nanobioscience Center at Arizona State University whose Director has expressed interest in collaboratively developing technologies in the areas of highly sensitive spectroscopy and integrated nanodevices for Life Sciences applications. At the international level we will collaborate with research academic centers in South America, starting with research groups at the National University of Engineering, Lima, Peru.

- **Promote University-High School partnerships.** The PI will continue to conduct outreach activities at high school, helping science teachers in their mission of enhancing scientific literacy of wider audiences. Based on the PI’s own experience, these activities have beneficial ripple effects in motivating vocational service (PSU students, accompanied by the PI, will volunteer to deliver technical presentations, as has happened for the past three consecutive years), in creating awareness of diversity (urban and rural high schools will be visited) and in cultivating high-school student interest in the area of science (high school students have
volunteered to do summer internships at the PI’s laboratory for the past two years). The PI views this activity as a long term investment since it also helps to attract high-school students into nanotechnology programs at PSU.

The goals of this Career program fit well within the ongoing developmental plan of the Physics Department at PSU to become one of the region's foremost centers of nanotechnology (one Endowed Chair and 4 new faculty members with expertise in Electron and Optical Microscopy have joined the department in the last 3 years). Furthermore, the physics department will enthusiastically provide support, in the form of a Teaching Assistantship, for one participating graduate student as a way to ensure the success of this Career program.

The above mentioned Career goals are also delineated within PSU’s institutional goal of becoming an Urban University\(^1\) (i.e. an institution that cultivates the formation of partnerships with regional and community agencies). In this respect, the PI is currently encouraging a strong PSU presence at Molalla High School, an institution located in a rural area outside Portland and having a diverse ethnic population. For the latter activity the PI has received support from the PSU Academic Center for Academic Excellence (CAE) through its Mini-Grant program. More recently, the CAE selected the PI as a team-member of the 2003-STRT program, a Carnegie-funded program aiming to support community service activities.\(^2\) This Career program also embraces the initiatives of PSU’s President toward diversity\(^3\) (the PI will recruit at least one participant student member from a minority group) and internationalization\(^4\) (the PI will promote his collaboration with research institutions in South America as a vehicle that can contribute to stabilizing the economies of developing countries).

**B. MAJOR RESEARCH EFFORTS**

**Near-field Optics as a general platform to study dynamic processes in semiconductors and the kinetics of biological macromolecules when constrained in nanostructures.**

The theme underpinning this Career program is the study of the dynamics of material constituents (when responding to an optical or electrical stimulus) using Near-field Optical Imaging (NFO). The reason for pursuing NFO lies in the opportunities it offers for extending the applications of conventional optical microscopy into the (until very recently inaccessible to optics) nanometer scale domain. Furthermore, NFO preserves the inherent polarizing, non-invasive, spectroscopic and high temporal resolving capabilities of conventional microscopy (a formidable set of integrated characteristics indeed) that are absent from other high-resolution techniques\(^5\). The strong impact of optics on science, engineering and national needs\(^6\) increases the relevance that this Career research program can bring to fundamental microscopy as well as to the education of PSU students.

Fundamental research combined with fabricating integrated nano-optical/mechanical devices characterize this Career program. Both aspects are reflected in the two near-field optics applications that are addressed in this proposal: \(a\) The first is near-field imaging with a **single probe**, in which a subwavelength-sized aperture is raster-scanned along a sample surface, interrogating the material in a pixel-by-pixel fashion. To prevent the probe from making contact with the uneven features in the sample’s topography, an electronic feedback mechanism is employed. The PI will use this modality to **study carrier dynamics** in bulk semiconductors and nanocrystal semiconductors (quantum dots), an application described in Section B.1 below. \(b\) The second aspect, still elusive to near-field optics, is imaging moving species. The single probe imaging modality does not work here simply because of the relatively slow response in the
electronic feedback circuit (which typically has ~1 kHz bandwidth) to follow moving objects.

The marriage of optics with electronics finds a limit here. An alternative is to integrate optics
with micro-mechanics. Driving the moving species, macromolecules for example, through
microchannels and monitoring their dynamics using an array of near-field probes is the
alternative approach that this Career proposal will pursue, as described in Section B.2. While the
PI’s research group will concentrate on fabricating the multi-probe near-field arrays (with the
students assimilating hands-on experience in Optical-MEMS technology), the microchannels will
be provided, through a research collaboration, by the Applied Nanobioscience Center - Arizona
State University.

B.1 STUDIES OF CARRIER DYNAMICS IN SEMICONDUCTORS

This section starts by describing the optical setup for measuring carrier lifetimes of electron-
hole pairs in bulk semiconductor materials as a particular example that provides the rationale for
implementing time-resolved near-field imaging. The signal levels involved in these experiments
are calculated based on the theory of “Free-Carrier Absorption.”7 Extrapolating these calculations
to the case of a single nanocrystal, the PI calculates that a signal level sufficiently greater than
the expected noise level of the employed instrumentation will be obtained. The implication of this
calculation is clear: time resolved near-field optics can become an important analytical tool to
study transient phenomena including excitons confined in silicon, and by extension to other
semiconductor materials, e.g., quantum dots.8,9 The study of quantum dots is a very promising
field of research with multiple potential applications.10,11,12 For these reasons, time-resolved near
field optics constitutes one of the central motivations underpinning this Career proposal.

Carrier lifetime measurement of e-h pairs by purely optical means (pump-probe method)
using single probes

Carrier lifetime constitutes one of the most important parameters used to characterize bulk
semiconductor materials.13 Charge carriers excited to the conduction band (by optical or electrical
means) remain there for a lifetime, $\tau$, before returning to the valence band (see Fig. 1). The
lifetime depends significantly on material quality: a variety of defects are capable of promoting
the relaxation and thus reducing the lifetime.14

In an NFO setup, light is delivered through a nanometer-sized aperture whose vertical
position (controlled by an electronic feedback mechanism15) is maintained 10 nm away from the
sample while being scanned laterally across the sample’s surface. At every (x,y) coordinate of the
probe’s lateral position a near-field measurement involves three steps:

a) With a 2-mW pump-beam coupled into the back of the NFO tapered probe, a flux of $\sim 10^{11}
photons/s exits the aperture ($a \sim 100$ nm) and generates a steady state population of excess
carriers, $N$, in the sample region just beneath the probe ($N \sim 10^{16}$ carriers/cm$^3$ while the pump-
beam is ON).16 When the pump-beam is switched OFF, the excess carrier population decreases
with time due to recombination processes.

b) An infrared (IR) laser beam ($\lambda_{IR} = 1150$ nm, power $\sim 1$ mW) is coupled into the same probe. In
the region just beneath the probe-aperture, the incident IR beam (input flux density $I_n \sim (10^{11}
photons/s)/a^2 = 10^{21}$ photons/cm$^2$ sec) interacts with the time-dependent excess of the carrier
population, causing the IR-transmission signal to change accordingly. The absorption of
incident IR photons by free carriers is referred to as the “free carrier absorption” process,
which, for silicon, has an absorption coefficient given by $\alpha_{FC} = K N \lambda_{IR}^{-2}$ with $K=3.5 \times 10^{-18}
cm^2/\mu m^2$. For $N=10^{16}$ carriers/cm$^3$ the expression above gives $\alpha_{FC} \sim 0.1$ cm$^{-1}$.18 The free
carrier absorption model provides an estimate of the expected change \( \Delta \phi \) in infrared transmission intensity (between the ON and OFF states of the pump beam) on the order of

\[ \Delta \phi \phi \sim \alpha_{FC} \Delta z = 10^{-5}. \]

This value sets the maximum noise level allowed in the detection system: changes in the infrared signal of a magnitude of one part in \( 10^5 \) should be detected.

Since we are considering that 100 nW of incident radiation is involved in the experiment, a detection system of \( 10^{-4} \) nW/(Hz)^{1/2} noise density level will do the job.

\[ \Delta \phi \sim \tau \]

\( \lambda \)

\( \phi \)

\( \alpha \)

\( \Delta \)

\( \phi \)

\( \alpha_{FC} \)

\( \Delta z \)

\( \alpha_{FC} \Delta z \)

\( \Delta \phi \phi \sim \alpha_{FC} \Delta z = 10^{-5}. \)

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c) Monitoring the decay of the population of excess charge carriers. Although real-time monitoring of the decay would be preferred, synchronous detection of \( \Delta \phi \) (for a given frequency of the amplitude-modulated pump beam) will be implemented instead to overcome the typically low signal-to-noise ratio that results when analyzing bulk materials (due to the diffusion of carriers). Depending on the homogeneity of local carrier lifetimes across the sample, a chosen modulation frequency might be too fast for recombination of a full population of electron-hole pairs to take place between cycle pulses, thus giving a relatively low signal \( \Delta \phi \). At another \((x,y)\) location the opposite may occur if the local lifetime is short compared to the periodicity of the cycle, with e-h pairs having more than sufficient time to relax and the corresponding signal \( \Delta \phi \) will be comparatively higher. This procedure allows mapping the sample regions according to their local lifetimes, as the probe scans the surface sample. Studies on the dynamic response of carriers to optical excitation can be obtained by probing the sample at different modulation frequencies.

Previous results of carrier lifetime studies by near-field imaging in bulk silicon

Preliminary results are shown in Fig 2. The most interesting feature is that the near-field image contrast (based on the synchronous detection of \( \Delta \phi \)) changes as the frequency of the amplitude-modulated visible light crosses a material-dependent frequency \( f_o \), equal to \( \sim 100 \) Hz in
this case. To link these near-field measurements with macroscopic observations, one can associate with this particular crossover frequency a characteristic time constant $\tau_0 \equiv 1/(2\pi f_0) \approx 1.5$ ms. It is interesting to notice that this value is very close to the 1-ms lifetime measured independently by a standard laser/microwave technique. The correlation between these macro and near-field measurements is very encouraging and will be further investigated as part of this Career program. For this purpose new state-of-the-art silicon samples will be provided by the Silicon Wafer Engineering and Defect Science Center (SiWEDS). Dr. George Rozgonyi, the Director of the Center, has committed his support to this Career program. The benefits of this collaboration with the SiWEDS at Carolina State University will be mutual. Indeed, Dr. A. Karoui, Research Associated of the Center, will pursue the detection of excess population of carriers by electrical means, which complements well the fully optical detection technique pursued by the PI in this Career program.

Another interesting observation in the time-resolved near-field studies referred to above is that carrier diffusion does not appear to limit lateral resolution in studies of bulk materials, although it puts a more severe demand on the sensitivity required by the electronic imaging/detection system. Theoretical modeling, although undertaken in the context of the Optical Beam Induced Current, supports this conclusion. This Career program will explore further these findings by providing additional experimental evidence.

**Time resolved near-field imaging the dynamics of e-h pairs in silicon nanoparticles (in the weakly and strongly confined regimes).**

Extending carrier lifetime studies from bulk samples to nano-particles offers many opportunities to study the new interesting physical phenomena that arise due to the spatial motion constraints to which carriers are subjected. For example, luminescence from conglomerates of silicon nanoparticles has been found to be greater than from bulk crystals, a phenomenon that is explained in terms of the lower probability for the e-h pair to undergo an Auger process or to encounter non-radiative centers (as it happens in bulk-silicon where the e-h pair has the opportunity to migrate over macroscopic distances). Notice that this phenomenon is explained even without the need to invoke the quantum mechanical behavior of nanoparticles (namely the particle-size dependence of the band-gap), which illustrates the wealth of opportunities that the studies of nanocrystals offer. The advantage that the research in this Career program offers over previous studies is that the **dynamics of e-h pairs in single particles** will be analyzed. Recent studies involving single nanocrystals have revealed physical aspects never seen before in the studies of conglomerates. The main question that this proposal addresses, however, is whether or not the time-resolved near-field technique described above will have sufficient sensitivity to characterize nanostructures. Order-of-magnitude calculations, shown in the following, indicate that the answer is affirmative.
Let’s consider first a silicon particle of radius \( R = 50 \) nm. Since the Bohr radius \( R_B \) of e-h pairs is on the order of \( R_B \approx 5 \) nm, we are then in the weakly confined regime \((R > R_B)\) where the e-h Coulomb interaction is large compared to their kinetic energy\(^{29}\) and the excited states (excitons) are of the hydrogen-type. It has been found that at even these small dimensions the physical properties of particles still resemble the bulk ones\(^{30,31}\) a fact that justifies using in our calculations the bulk value for the absorption coefficient, \( \alpha \approx 10,000 \text{ cm}^{-1} \) at \( \lambda \approx 500 \text{ nm} \).\(^{32}\) Coupling 1 mW of visible light \((\lambda = 500 \text{ nm}, h\nu = 2.47 \text{ eV})\) into the NSOM probe will result in \( \sim 10^{10} \) photons/sec being deposited into a particle of volume \( \sim 10^{-15} \text{ cm}^3 \).\(^{33}\) Assuming a carrier lifetime of \( \tau = 1 \text{ ms} \), we obtain \( N = 10^{22} \text{ carriers/cm}^3 \) and a corresponding free carrier absorption coefficient \( \alpha_{FC} = K N \lambda_{IR}^2 \approx 10^4 \text{ cm}^{-1} \), which gives \( \Delta \phi / \phi \approx 0.1 \) for the fractional change in the transmitted infrared signal.\(^{34}\) This sensitivity in \( \Delta \phi / \phi \) is many orders of magnitude higher than the \( \Delta \phi / \phi = 10^{-5} \) calculated in the paragraphs above for bulk silicon. The advantage comes from the fact that effects of diffusion are absent when interrogating a nanoparticle (a factor that places too much strain on the apparatus sensitivity when analyzing bulk material) since all the charges remain inside the particle and are available for interacting with the incident infrared light beam. These order-of-magnitude calculations lead us to believe that the time-resolved near-field technique will enable us to characterize these single nanocrystals very accurately.

The analysis of particles in the strongly confined regime \((R < R_B)\) will require particle sizes on the order of \( R = 5 \) nm. Although we could still assume that a density of \( 10^{22} \) carriers/cm\(^3\) will be excited in the nanoparticle\(^{35}\), the resulting value for \( \Delta \phi / \phi \approx 10^{-2} \) could be too demanding for a detection system having a \( 10^{-4} \text{ nW/(Hz)}^{1/2} \) density noise level (this figure is for a two-stage amplifier with a \( 10^8 \Omega \) gain-resistor that the PI plans to build). The reason is that there are only \( \sim 5 \times 10^5 \) atoms in a 10 nm diameter silicon particle and \( 10^{-4} \text{ nW} \) is equivalent to \( \sim 10^5 \) photons. We would then be on the border of the detection system. One solution would be to build a preamplifier with a higher resistor gain, although at the expense of lower frequency bandwidth. Thus, in principle, it is possible to extend the free carrier detection into the strongly confined regime \((R < R_B)\). However, in the regime of strong confinement the band-gap of the nanoparticles increases and transitions in the visible range are observed. For this reason, we additionally propose to detect the dynamics of carriers with an avalanche photodiode detection system when studying the dynamic of e-h pairs in the strongly confined regime.

**A continuity perspective of this Career program:**

**Combined optical/electrical characterization of single-electron devices**

A plausible argument can be raised, questioning the necessity for NFO to characterize nanoparticles. Given the current progress in self-assembly sample preparation methods, nanoparticles could be isolated with high controllability of their distribution density and, thus, be analyzed more rapidly with far-field optic methods. Indeed the advantage of far-field optics over NFO in those cases where the isolation of material constituents can be afforded, has already prompted the PI to search for alternative methods to implement near-field parallel imaging approaches, a subject that is in fact addressed in Section B.2 below. What is important to emphasize here, however, is that the near-field technique (the one described in the paragraphs above) is not intended to compete with far-field optics in applications where the latter might be better suited. Rather, it constitutes the first step of a more futuristic approach that aims to characterize **in situ** the functioning of nanoelectronic devices (they have subwavelength dimensions, cannot afford to be disassembled and, therefore, far-field optics are not applicable to testing its individual components because of the \( \lambda / 2 \) limit on resolution). As an example, we
briefly describe below a very possible scenario where the near-field time-resolved technique can find a niche application, which is **testing single-electron devices**. The PI wants to clarify at this point that the brief description to follow is included here with the sole purpose of providing a perspective on a future development the possibility of which will be explored during this Career program (in year-5 we plan to purchase a capacitance sensor and start exploring this application). Near-field optical/electrical analysis of single-electron devices deserves a separate project in itself; to attempt to achieve it fully here could overtax the resources of this Career program and compromise the completion of the other objectives. I describe the project here, however, as a way to provide a sense of the direction of my future research activities.

An outstanding accomplishment in nanoelectronics is represented by the recent experimental demonstration of a single-electron non-volatile memory device that operates at room temperature. The single-electron device in Ref. 37 is very similar to the one shown in Fig. 3a, except that the authors made the floating gate very small (7 nm square by 2 nm thick), causing the energy necessary to store an additional charge to be much greater than the thermal noise, kT. The 5-second charge storage time (very short by all means) of this device leaves room for additional investigation to improve device performance. Fig 3b suggests using the metal-coated near-field probe as the gate electrode, which can be used **in situ** to **characterize the floating gate optically and electrically**. Short electric pulses can be used to charge it, or, with all the voltages turned off, we can proceed with the optical characterization described in the preceding sections of this proposal. Full characterization can be achieved by incorporating a capacitance sensor to track the capacitance variations that develop in the channel as more electrons are deposited in the gate. Complementing near-field optical microscopy with capacitance microscopy, both performed with the same probe, could provide a powerful tool for analyzing single-electron devices.

**Figure 3** (a) Schematic arrangement of the components of a non-volatile memory device. (b) near-field probe functioning as a gate electrode.

**Figure 4** Prospective future development: Near-field Optical/Capacitance Microscope. a) and c) Schematic of a combined near-field/capacitance experimental setup. The NFO probe serves both as capacitance electrode and light source. b) Capacitance as a function of the metal-semiconductor dc bias voltage. The diagram also shows capacitance variations induced by an ac voltage, synchronously detected with a lock-in amplifier and a capacitance sensor with 10⁻²⁰ Farads/(Hz)¹/² sensitivity.

swept from positive to negative values causing the capacitance of the MOS structure to change, as shown in figure 4b. Aided by theoretical models, this C-V curve allows to determine the charge...
carrier density in the semiconductor-insulator interface, an important factor in fabricating field effect transistors.

B.2 MONITORING THE DYNAMICS OF SINGLE MOLECULES CONFINED IN NANOSTRUCTURES

Fabrication of near field multi-probes: Optical/MEMS

An elusive area in near-field optics applications is the analysis of moving molecules. To put the progress of near-field imaging in some perspective, successful experiments (using single probes similar to the one shown in Fig. 1) have been performed with isolated single molecules dispersed at fixed positions on a surface substrate, including measurements of their electric dipole orientation\(^40\) and fluorescence lifetimes.\(^{41,42}\) However, in such applications where the isolated molecule coverage can be controlled, the superior data acquisition speed of conventional (far-field) optical techniques would be more convenient.\(^{43}\) The relatively slow speed at which single probes can be scanned over a sample surface, due to the limited bandwidth of the electronic feedback that controls the probe’s position, has prevented, so far, near-field analysis of moving objects. A vast number of applications involving moving molecules and requiring nanometer lateral resolution await major developments.\(^44\) This Career program presents a unique opportunity for the PI to exploit his background in NFO and explore new ways to analyze moving objects rapidly and at high lateral resolution. Specifically, the PI will incorporate Micro-Electro Mechanical Systems (MEMS) technology\(^{45,46}\) into his Career program to fabricate integrated near-field/microfluidic devices for applications involving rapid screening of biomolecules. A collaboration with the Applied Nanobioscience Center, Arizona State University, who will provide the microfluidic structures (in which molecules will be transported by electrophoresis), will allow the PSU group to concentrate on fabricating a multi-probe near-field apparatus. The idea driving this effort is somewhat simple: rather than bringing a single sharp probe toward a sample, let’s bring the sample (the molecules) toward an array of stationary near-field probes (using properly microfabricated channels), thus by-passing the need for electronic feedback to control probe-sample distances.

A perspective on why we are pursuing MEMS: Current technological need for integrating Optics into MEMS

MEMS is an evolving technology that capitalizes on the excellent mechanical characteristics of silicon\(^47\) to fabricate electro-mechanical actuators of micrometer dimensions. One approach in MEMS devices fabrication involves micro-machining ”bulk” silicon, a process that exploits the preferential chemical etching (a ”carving process”) that silicon material undergoes across its different crystallographic planes. This process allows generating tri-dimensional structures under precision control. Complemented with existing photolithographic techniques (borrowed from well established integrated circuit technology), large and cheaper quantities of micro-mechanical devices can be produced at once. The field of MEMS has developed rapidly. In fact, some products are already on the market: accelerometers for air-bag deployment and resonant membranes used as pressure sensors, for example.

A dramatic enhancement to the ”bulk” silicon micro-machining capabilities is surface micromachining technology.\(^{48}\) In a process that involves sequential deposition of polysilicon material and silicon oxide layers, stand-alone three-dimensional movable structures are fabricated after chemically etching the oxide. An example of this process is the fabrication of movable mirrors (as the
one shown in the figure at the left) which find applications in controlling data traffic (re-directing information carried by optical fibers) in optical networks.\textsuperscript{49}

Currently, MEMS devices are reaching nanometer dimensions and are thus being renamed NEMS (nano-electro mechanical systems).\textsuperscript{50,51} This technology is well suited for a host of applications in biotechnology and biomedicine. Nano-channels, in particular, have potential applications in fields that require controlling the flow of small volumes of fluid, including DNA separation technology (electrophoresis).\textsuperscript{52,53,54} Adding analytical capability in the form of optical spectroscopy would make these devices unique. This Career program capitalizes on the current interest for integrating Optics with NEMS to enhance the analytical capabilities of NEMS devices by exploiting the inherent spectroscopic, high temporal resolving and polarization properties of light.

**What this Career program objective addresses:**

**Integrating Near-field Optics with MEMS/NEMS devices**

The overall idea in this near-field optics application is to use NEMS microfluidic technology as an enabler to properly manipulate the samples under analysis (moving macromolecules, cells, polymers, or simply different chemical substances pumped through micro channels.) By driving the sample (the moving molecules) beneath a stationary array of near-field probes, the typically slow electronic feedback to control probe-sample distance (as required when using single probes) is circumvented. Consequently a multi-probe near-field/microfluidic analysis process is conceptually faster. Our research infrastructure in Optics and Electronics (these are the two backbone disciplines involved in NFO, as described in Section B.1 above) provides an opportunity to make an effective impact in the field of MEMS. Our collaboration with the Applied Nanobioscience Center (ANC) at Arizona State University could not have been much more opportune: their willingness to provide MEMS-microfluidic devices will allow the PI to concentrate on the integration with optics. In this endeavor the PI is also collaborating with Dr. Lemmy Meekisho, Associate Professor in the Mechanical Engineering Department at PSU, who has developed and taught a course on MEMS at PSU. Dr. Meekisho and I have submitted a joint proposal to the Department of Defense,\textsuperscript{55} in which we outlined our interest in assimilating MEMS into our research program. The PI (A.L.R.) has also received institutional seed-support through the PSU “Faculty Enhancement” award in 2003 to develop the area of MEMS.

**Getting started: Fabricating integrated near-field/microfluidic devices**

As an initial step, and considering the relatively lower budget cost involved, the PI plans to construct, first, near-field probe arrays at PSU using bulk micro-machining procedures, which will be furnished with MEMS microfluidic devices currently built at the ANC. The applications include fast screening of moving macromolecules at high lateral spatial-resolution. The functioning of the device involves driving molecules toward stationary near-field probe arrays, is schematically shown in Fig. 5. We aim to combine the high lateral spatial-resolution capability of near-field optics and the convenience of using micro-channels to constrain macromolecular motion in order to screen macromolecules very rapidly, and at the same time, at high lateral resolution. Fabricating devices with multiple nanometer-sized features to exploit near-field optics effects is currently an active field of research.\textsuperscript{56,57,58} Encouraging results in detecting moving molecules at high lateral resolution have been obtained with multiple aluminum slits fabricated with e-beam lithography.\textsuperscript{59} Here we suggest an alternative lower cost construction of sub-
wavelength-slits that uses capabilities already existent at PSU (near-field optical measurements at the PI’s laboratory and the focused ion beam housed in the Physics department).

Fig. 5 Getting started. Schematic of a near-field probe array device for parallel (rapid) near-field imaging of bio-molecules. Guiding DNA molecules through the channels increases the screening speed, while the narrow slits (a<λ) of the near-field probes provide the high lateral resolution. Molecules will be optically excited through slit apertures as they travel through the microchannels. Far-field detection in transmission, not shown in the figure, is achieved with an intensified CCD camera. Top: Fabricating the near-field array comprises anisotropic chemical etching and definition of sub-wavelength slit apertures with the focused ion beam that is housed in the PSU Physics Department. Bottom: Front and aerial views of the near-field probe array and micro-channels (the latter to be fabricated in collaboration with the Applied Nanobioscience Center at Arizona State University).

Training PSU students at the Washington Technology Center MEMS foundry

A crucial aspect in fabricating nanodevices is interfacing them with the macroscopic world. In the particular case of microfluidics for example, even if channels of nanometer cross section were fabricated, efficient insertion of DNA molecules into the channels may become a challenge. A gradual transition from macro to nano-sized channels dimension is likely key to render these devices useful. This aspect serves to motivate this Career program to train PSU students in MEMS microfluidic fabrication with the focused objective of harnessing the techniques that make it possible to interface micro- with nano-channels. Although we will concentrate on the technical aspects of fabricating these devices, this area is fundamentally fascinating in itself. It brings to the discussion concepts of confinement-induced entropy (large molecules recoil toward higher entropy regions), which will surely heighten the sense of learning and discovery in our students. The training activity at the Washington Technology Center offers an opportunity for PSU students to acquire a superb professional training in current nanotechnologies. Because many of the procedures involved in fabricating these nano/micro interface devices (PECVD oxide deposition, reaction ion etching, etc) are well established techniques, our students will be able to assimilate them quickly. The impact of student training in this proposal is that it will contribute to developing better strategies of integrating near-field optics into nanofluidic devices, leading to the design, construction and implementation of a high throughput analytical devices.

C. INTEGRATING RESEARCH AND EDUCATION.

This proposal aims to provide PSU students opportunities to acquire a comprehensive education with components in vocational service to society and awareness of diversity. To reach this goal, however, a strategy different from simply overloading our students with additional courses will be required. Attending lectures on Ethics (for example), while being a welcome activity, may not be sufficient to cause a long standing effect in students’ minds. In addition, given our graduate students’ habit of working long hours and constantly feeling pressured to get results for their highly demanding advisor, requiring them to register in additional courses may backfire on the noble intention pursued by the proposal. As an alternative,
the PI’s own experience suggests that an activity key to providing graduate students with an awareness of diversity and service is to earn first their willingness to disseminate knowledge in the areas of Optics and MEMS related to their research work at local high schools.\textsuperscript{64} I provide to my students a logical rationale in an attempt to win their enthusiasm. For example, I explain that the synthesis of knowledge in a short, clear and effective presentation in front of a large audience is an ability that requires practice and that it has a long term rewarding effect on a professional career. Additionally, the skill of speaking clearly before a large group could be the difference in being offered a long desired job. Upon evaluating these benefits our students see a ‘practical’ reason to participate. The results of this approach so far have been very rewarding. After their participation they are generally happy to have been engaged in an activity that, even though was originally motivated for a personal benefit, ended up being a service to society as well. Furthermore, these technical presentations, while helping the PI to build partnerships between PSU and local high schools, produce an additional effect: students of diverse ethnic origin (see figure 6) learn to work together towards a common objective.

Why to target a high school? Why not to approach, for example, the industrial sector, which will certainly be more interested in being aware of current nanotechnology developments? Is it because the high schools constitute an easier target? Not at all. The PI fully recognizes the importance of getting the industrial sector on board in his research agenda. In fact, Dr. La Rosa has participated in a PSU-sponsored project\textsuperscript{65} “Let Physics Serve the City”, coordinated by Dr. Peter Moeck (and collaborator of this Career program), which had as one of its objectives building a closer relationship with the industrial community around Portland. The emphasis of this Career program in high school education, however, has its roots in the, so far, nationwide isolated efforts to generate science education reforms in high school and undergraduate education.\textsuperscript{66,67,68,69,70} As Leon Lederman, a Nobel Prize winner in physics, put it bluntly: a time traveler from the year 1899 would be amazed by our advances in technology but “the only place in which this visitor would be comfortably at home is in most of our high schools.”\textsuperscript{71} The PI feels compelled to collaborate with high school teachers in their mission to enhance scientific literacy. As a starting point the PI has targeted Molalla High School where he will collaborate with Ms. Emmely Briley, an enthusiastic Physics Teacher with whom Dr. La Rosa has already submitted a joint proposal.\textsuperscript{72} Other envisioned activities include summer internships awards for high school students, presentation of their summer work at high school competitions, and elaboration of an experiment manual that will facilitate the reproduction of optical experiments at other high schools.

Working along PSU’s institutional goal of becoming an Urban University (i.e. an institution that cultivates the formation of partnerships with regional and community agencies),\textsuperscript{73} and in coordination with the Center for Academic Excellence (CAE) at PSU,\textsuperscript{74} Dr. La Rosa plans to continue promoting a University-High School partnership, that, as explained above, stimulates learning (in graduate, undergraduate and high school students), contributes to effectively
communicating scientific knowledge to a broader audience, awakes a sense of vocational service to society, and develops awareness of diversity, all of this in an integrated manner that benefits both institutions. The PSU’s CAE and the Provost Office have awarded the PI seed grants to fulfill this mission.

**Provide PSU students opportunities to acquire professional writing skills.**

The PI realizes that developing writing skills is an aspect in student education largely ignored in most graduate education curricula. Such a deficiency represents a great disadvantage especially to physics majors who plan to pursue an academic career. This problem becomes even more relevant if we take into account that it is a very competitive world in which to win funding for a research program. Under the logo “better writing skills better funding opportunities”, the PI and Dr. Carol Burnell, the Writing Center Coordinator at PSU, have joined efforts with excellent mentors in writing (PSU student English majors) who will train physics majors, on a person-to-person basis, to acquire proficiency in grant proposal writing. This Career program will promote this activity during an equivalent of 3 summer sessions. Evaluating the success of this initiative will be measured by requiring the students to submit at least two proposals to a scholarship grant agency.

**International perspective.**

The PI views his collaboration with research centers in South America as an activity that, if it were more widely spread, could contribute to the process of **stabilizing the economies of developing countries**. Nanotechnology, expected to shape global economics in a near future, is going to increase the already wide technological gap between developed and developing countries (with its consequent social implications). Sensitive to the implication of these events, one objective of this research program is to promote the assimilation of near-field optical technologies (currently in its early stages of development at Dr. La Rosa’s Lab) by research centers in Peru. The Scientific Instrumentation Group at the National University of Engineering, Lima, Peru has agreed to collaborate with the PI in this mission and will build microscope mechanical stages and electronic prototypes (inherent part of near-field optical microscopes) while disseminating such knowledge nationwide. We expect to establish bi-annual visits to each group’s laboratories. Peruvian researcher will benefit from **in situ** training in scanning probe microscopy. PSU will benefit from the know-how skill developed by the Peruvian researchers, have access to well qualified professionals and enhance the international dimensions of Portland State University.

**D. PERSONNEL EXPERIENCE, PROJECT EVALUATION, and COLLABORATORS**

Dr. La Rosa has hands-on experience in the design, construction and implementation of near-field scanning optical microscopes. From 1993 to 1996, he was a graduate student member of the Precision Engineering Center at North Carolina State University (NCSU), which was one of the very first research institutions involved in NFO development. At NCSU he built every component involved in the functioning of a near-field optical microscope, which included probe fabrication, optical set-up with visible and near-infrared laser sources, modification of feedback circuitry of commercial electronic systems, and construction of sensitive electronic preamplifiers. After receiving his Ph. D. degree, Dr. La Rosa worked as Research Scientist at Firmenich Inc., a chemical company located in Princeton, New Jersey. He used scanning probe techniques to monitor the development of chemical sensory components as part of an artificial olfactory system (“electronic nose”) development. Dr. La Rosa also worked as a Consultant Scientist at the Center for Nanomachining Surfaces at the University of Delaware.
## Project Schedule and Milestones

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<tr>
<th>Year</th>
<th>1</th>
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<td><strong>Objective</strong></td>
<td>Assemble scanner head into the IX-71 inverted optical microscope</td>
<td>PSU students become regular users of the Washington Technology Center for MEMS device fabrication</td>
<td>Device fabrication: near-field multi-probe integrated with microfluidic devices</td>
<td>Build a partnership with the PSU Center for Academic Excellence. Collaboration with Dr. Kevin Kecskes, Director, Community-Based Learning</td>
<td>Internship at the Applied Nanobioscience Center - Arizona State University</td>
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<td></td>
<td>Assemble the Spectra Pro-750 spectrometer with the IX-71</td>
<td>Build and reinforce collaboration with the Silicon Wafer Engineering and Defect Science Center (SiWEDS) at North Carolina State University, the Nanobioscience Center at Arizona State University, and the National University of Engineering in Peru. Planned visits to each site, one institution per year.</td>
<td>Build a partnership with the PSU Center for Academic Excellence. Collaboration with Dr. Kevin Kecskes, Director, Community-Based Learning</td>
<td>Implement a capacitance sensor into the near-field microscope starts</td>
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<td>Continue implementing the “Student Electronic Station” at the PI’s laboratory</td>
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<th>Evaluation</th>
<th>Undergraduate student: construction of a two-stage preamplifier (10^8 gain/300 KHz bandwidth)</th>
<th>Master thesis “Quantum phenomena in nano-particles” Studies extended to small band-gap materials (where quantum phenomena arise at relatively larger size particles)</th>
<th>Completion of optical/microfluidic MEMS prototype (including methodologies to interface macro- and nano-channels)</th>
<th>First NSOM image showing sub-wavelength lateral resolution</th>
<th>Results published in scientific journals</th>
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<td>MEMS design with Coventor’s software posted on the PI’s website</td>
<td>Presentations on &quot;SPM and MEMS&quot; at high school classroom settings. PSU graduate and undergraduate students deliver the presentations</td>
<td>Presentations on &quot;SPM and MEMS&quot; at high school classroom settings. PSU graduate and undergraduate students deliver the presentations</td>
<td>SEM and TEM characterization (at PSU) of quantum dots samples in collaboration with Dr. Moeck</td>
<td>Presentations on &quot;SPM and MEMS&quot; at high school classroom settings. PSU graduate and undergraduate students deliver the presentations</td>
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<td>First NSOM probe fabricated with a the Focused Ion Beam at PSU</td>
<td>Master thesis “MEMS: micro-to nano-fluidic interface.” Supervised by Dr. Meekisho and the PI</td>
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<td>PI submits of a joint proposal with Ms. Emmely Briley the Science teacher at Molalla High School</td>
<td>Completion of the Instruction Manual “Low cost Implementation of Optical Telecommunication experiments” To be distributed to high school teachers</td>
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## COLLABORATORS

The implementation of this Career program wouldn’t be possible without the collaboration of excellent professionals from inside and outside PSU who generously have committed themselves to participate and work with the PI towards successfully completing the program:
Dr. George Rozgonyi, Director of the Silicon Wafer Engineering and Defect Science Center (SiWEDS) at North Carolina State University. Dr. Rozgonyi and the PI share the common interest in developing diagnostic tools for electrical and optical characterization of semiconductor materials. The SiWEDS Center has a long standing reputation in correlating the electrical, structural, and chemical properties of semiconductors materials. Samples with tailored characteristics (a key aspect in research studies) will be available for this Career through the Center and its 11 industry members.

Dr. A. Karoui, Research Associate at the SiWEDS, is joining efforts to pursue electrical/optical characterization of semiconductors in a near-field fashion. He is heavily involved in this project and will be in permanent communication with the PI. Dr. Karoui brings to this project his expertise in materials characterization (measurement carrier lifetime with far-field optical/microwave techniques), and the PI will help his group with matters related to near-field optical microscopy electronic instrumentation.

Dr. Frederic Zenhausern, Director of the Applied Nanobioscience Center at Arizona State University, who has focused interest in developing highly sensitive spectroscopy and integrated nanodevices for Life Sciences applications. Dr. Zenhausern has expressed interest in collaborating with the PI to interfacing near-field optics with microfluidic devices. The sensitive detection equipment requested in this proposal will greatly enhance this collaboration.

Dr. Peter Moeck, Assistant Professor in the Physics Department at PSU and expert in Electron Microscopy. Dr. Moeck will use the PSU’s Tecnai F20 Transmission Electron Microscopy to characterize the nanoparticles samples that the PI will use in his studies. As an initial step, he will share self-assembled InSb islands on GaSb and embedded InSb/GaSb quantum dots samples. While Dr. Moeck’s studies emphasize the structural and thermodynamic aspects influencing the fabrication of quantum dots, the PI’s studies will focus on the composition, energy levels, and defects of individual particles. This collaboration will be therefore complementary and of significant mutual benefit.

Dr. Lemmy Meekisho, Associate Professor in the Mechanical Engineering Department at PSU, is an expert in the field of micro-mechanical stress analysis. Currently he is interested in reliability issues involved in the fabrication of MEMS devices, which is the cornerstone of the collaboration with the PI. In addition to developing a new course on MEMS at PSU, Dr. Meekisho and the PI share responsibility advising one graduate student and have submitted one joint proposal.

Carol Burnell, Writing Center Coordinator at PSU, will coordinate the training of graduate students in technical writing proficiency. She will be key in providing the PI’s graduate students proficiency in technical writing, an aspect that typically does not receive enough attention, or is simply completely absent, in the curricula of most graduate programs.

Ms. Emmely Briley, Physics Teacher at Molalla High School. Ms. Briley brings to this Career her enthusiasm to be involved in educational initiatives, motivating her students to participate in summer internships and regional science contest events, and managing her time to submit joint proposals (as she has done with the PI in the past). Ms. Briley has volunteered to help editing the “Instruction Manual” that describes the Optical Telecommunication Experiments implemented by the PI’s graduate and undergraduate students.

Kevin Kecskes, Director of the Community-Based Learning, Center for Academic Excellence. Dr. Kecskes will provide guidance and support (through a variety of supporting programs routinely available from the PSU CAE) that will help implementing the scholar activities the PI has included in his Career program.